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Reliability of Optical Components for HEC DPSSL

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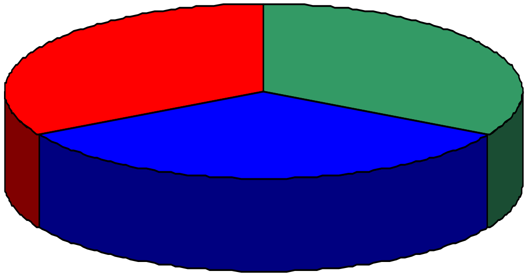
What is *Reliability* in optics?

Reliability implies

- **Prediction**: Theoretical or phenomenological model that can relate damage probability to laser operating conditions

- **Qualification**: Measurement system that is capable of non-destructive evaluation of optics

- **Assurance:** In-situ diagnostic systems capable of detecting the onset of damage to prevent catastrophic damage.



Reliability requires all three of these components to work together!

Terminology

<u>Damage</u>: We are actually referring to *laser-induced* **flaw** or an imperfection that can be seen or characterized by a diagnostic:

- human eye or microscopy
- scattering or interferometric techniques

<u>Initiation:</u> A **flaw** is created on/in an unblemished region of an optic with laser illumination

- usually due to the presence of a *<u>precursor</u>* *<u>defect</u>* of native material or an impurity
  - disturbances on molecular or lattice level are usually very hard to detect
- cleanliness

<u>Growth:</u> A **flaw** changes size upon exposure to laser illumination

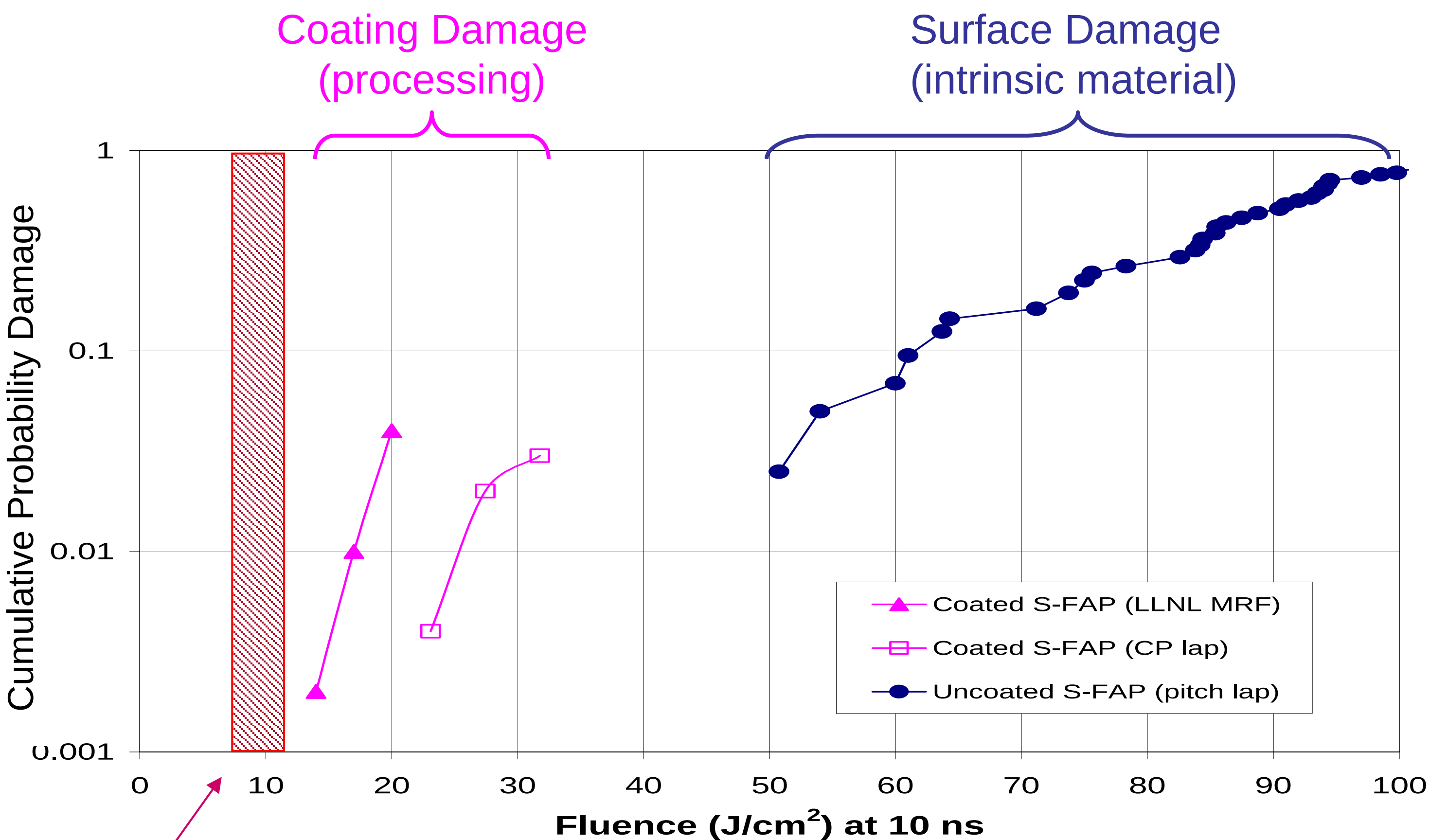
- may be compounded by presence of impurities
- can be an operational problem

** M. Spaeth, NIF, LLNL (2004).*

<u>Functional Damage:</u> Change in optics that will inexorably cause that optic or another optic to be removed from use

Recent Mercury damage

- Mercury Laser previously ran for >10^5 shots without ***laser-induced damage***
- As energy ramped to ~65 J, optics began experiencing damage



Bulk damage
during operations

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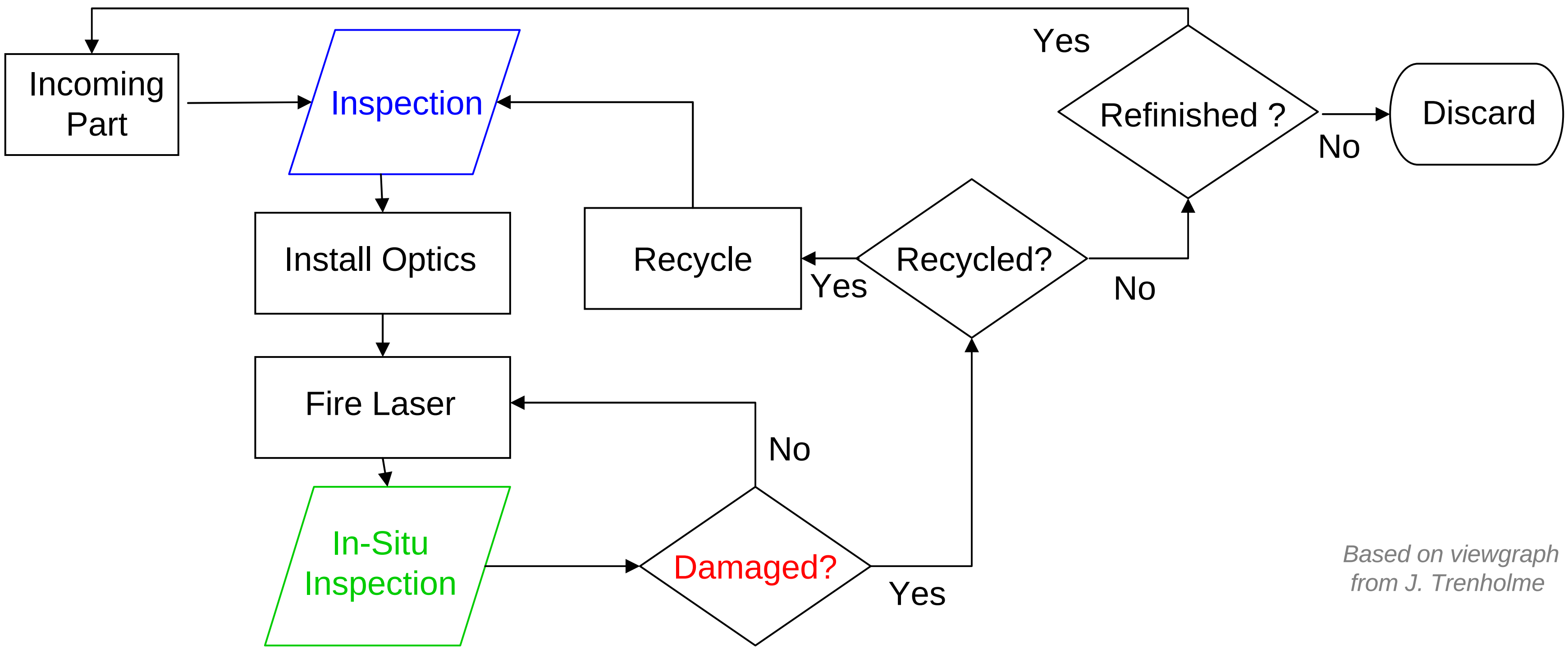
How does NIF deals with *reliability*?

The NIF strategy for meeting optics' performance goals consists of:

- **Data collection on flaw characterization and model verification**
- **Analytic modelling for making decisions**
- **Development of advanced optical materials and diagnostics**



Based on viewgraph from J. Trenholme

NIF accepts the fact that optics will degrade during laser shots and have established a process to maximize system performance

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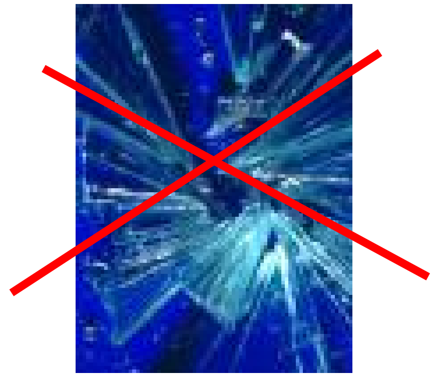
Challenges for Rep-Rated System

We cannot afford damage !!!



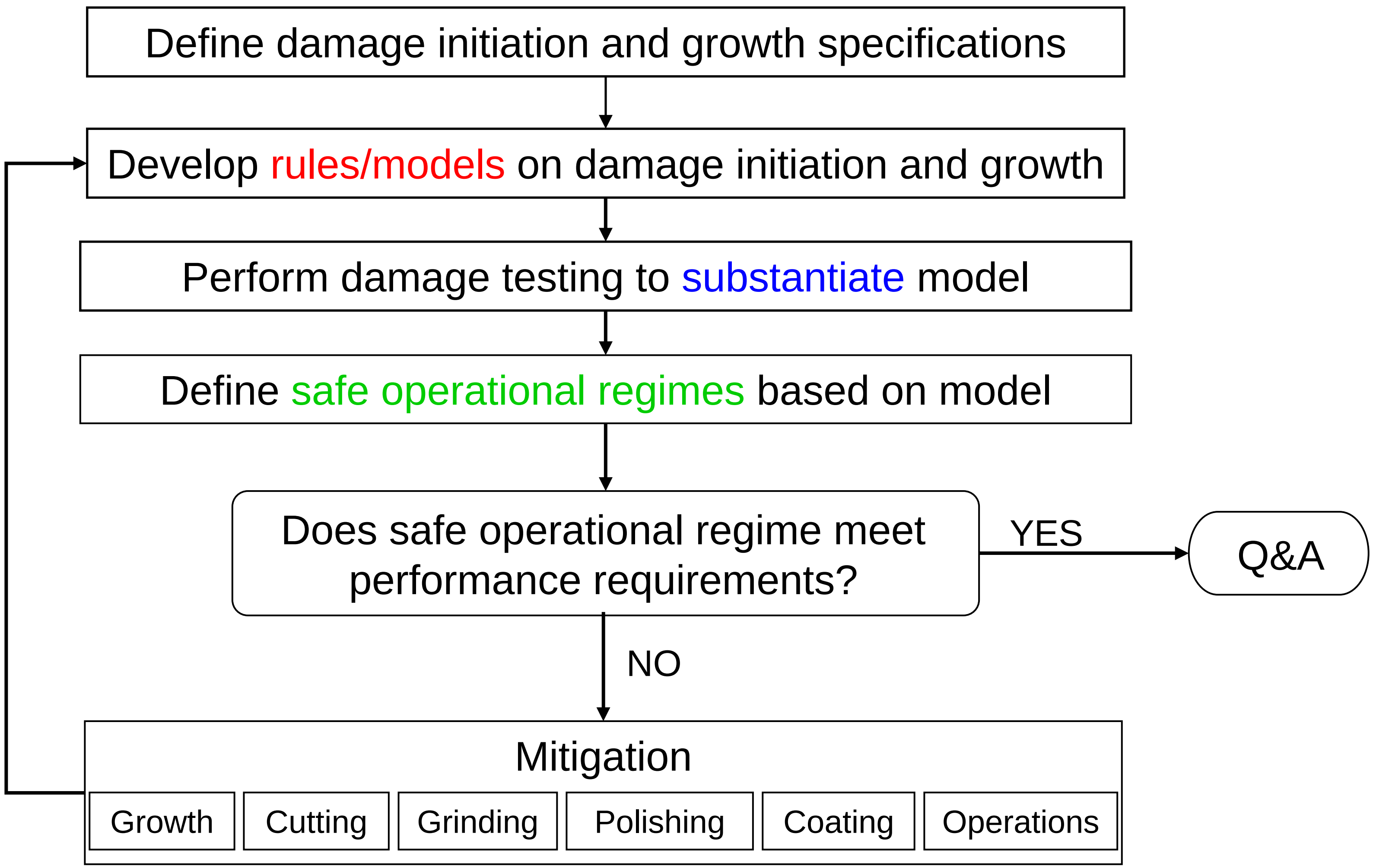
- ***How can we find a regime where no damage will occur?***
  - 10 Hz laser @ 8 hrs/day x 5 days/wk x 40 wk/yr = **5.8 x 10^7** shots/year
  - Over a 30 year lifetime = **10^9** shots

- ***How do we go about studying optic fatigue for 10^7 or 10^9 shots?***

We can start by learning from NIF's experience on damage, but there are additional challenges that we must take on by ourselves!

What’s our strategy?

GOAL: **10^9 shots without degradation in performance of various optics**



Define damage specification

Functional damage is driven by systems engineering:

1. How an initiated flaw site can change the beam downstream in a manner that can be detrimental to the system.
2. How an initiated flaw site can grow rapidly in time in such a manner that might become detrimental to the system.
3. How many initiated flaw sites can be tolerated with respect to beam obscuration or beam quality?

Damage definition must also incorporate operating conditions:

1. Laser wavelength (damage threshold is lower at shorter wavelength)
2. Laser pulse width (usually scales with $\tau^{(0.2-0.5)}$).
3. Changes in beam contrast (Max of N effect).
4. Changes in optic's quality, processing, handling, and environment.

What's our strategy?

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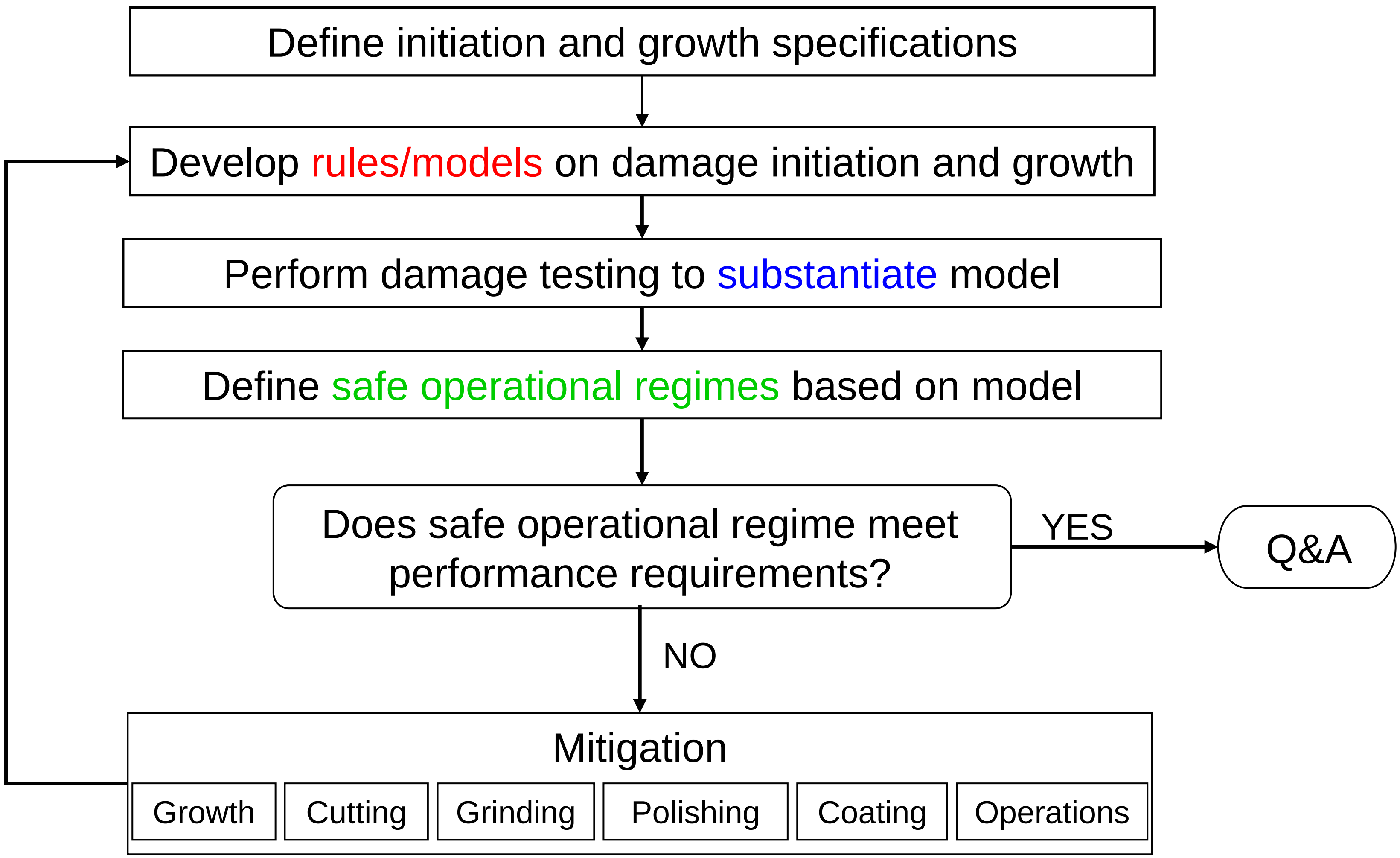


What do we know about laser-induced damage?

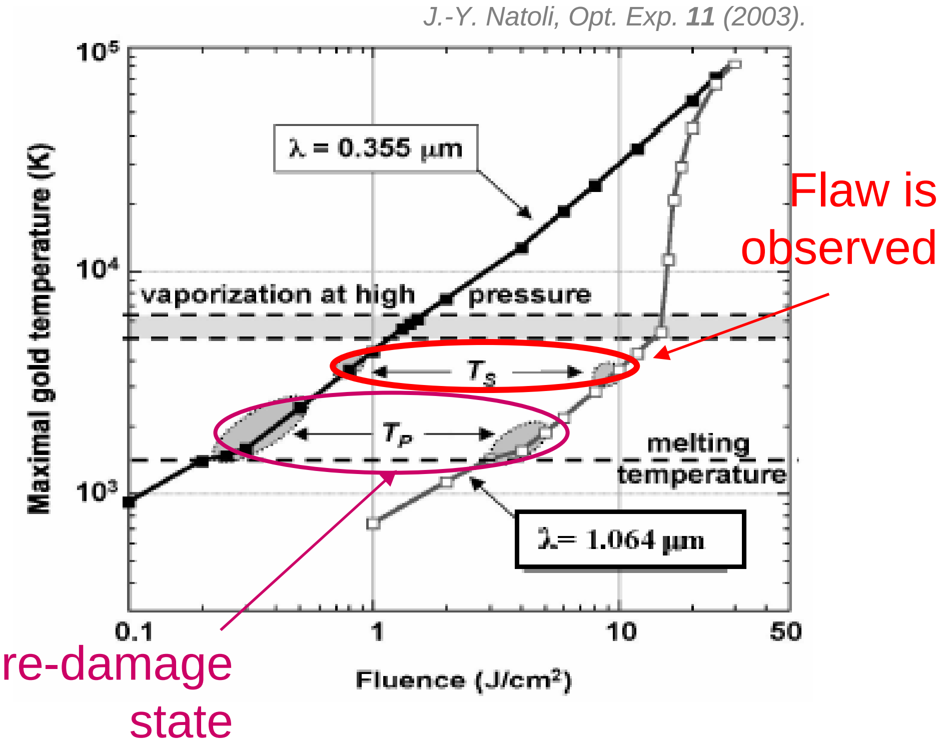
- Laser induced damage in transparent materials has been studied for decades, a lot has been learned about correlation of laser-induced damage but as of now, there is no proven theory on laser-induced damage.

J.-Y. Natoli, Opt. Exp. **11** (2003).

- One theory* centers on small absorbers as **nano-precursors**

- Staged studies by Natoli etc. showed modification of precursor sites *a priori* to creating *damage*

- Further laser radiation then causes the appearance of detectable *flaws*



*M. Spaeth, LLNL (2005)

*M. Feit, SPIE 5273 (2004)

Laser damage is believed to be caused by material imperfections such as small, nanoscale size absorbers acting as precursor sites

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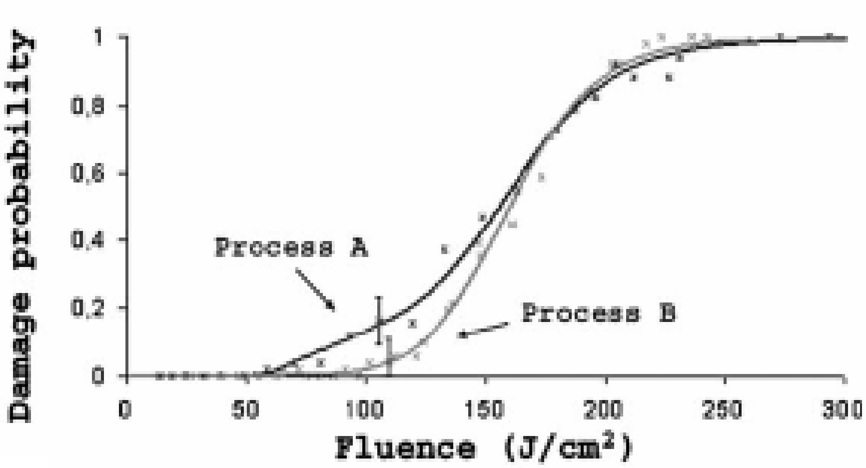
How do you analyze laser-induced damage?

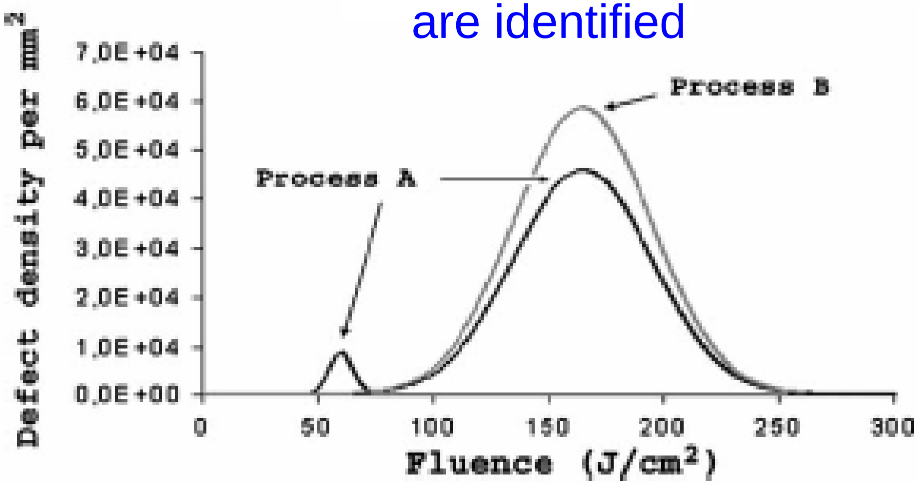
- Damage tests are conducted to obtain damage probability density function, $\rho(\phi)$
- Phenomenological models - fit to the data with parameters such as …

• **Damage threshold** (fluence at which flaws are formed)
• **Defect density** (precursors that initiate the flaw)
• **Damage threshold distribution** (different species or classes of precursors)
• **Shot number** (for damage fatigue studies).

Effect of polishing process



2 possible species of precursor are identified



H. Krol, Opt. Comm. ***256*** (2005).

Phenomenological models can be used to help interpret the damage test data and help identify possible causes of damage initiation

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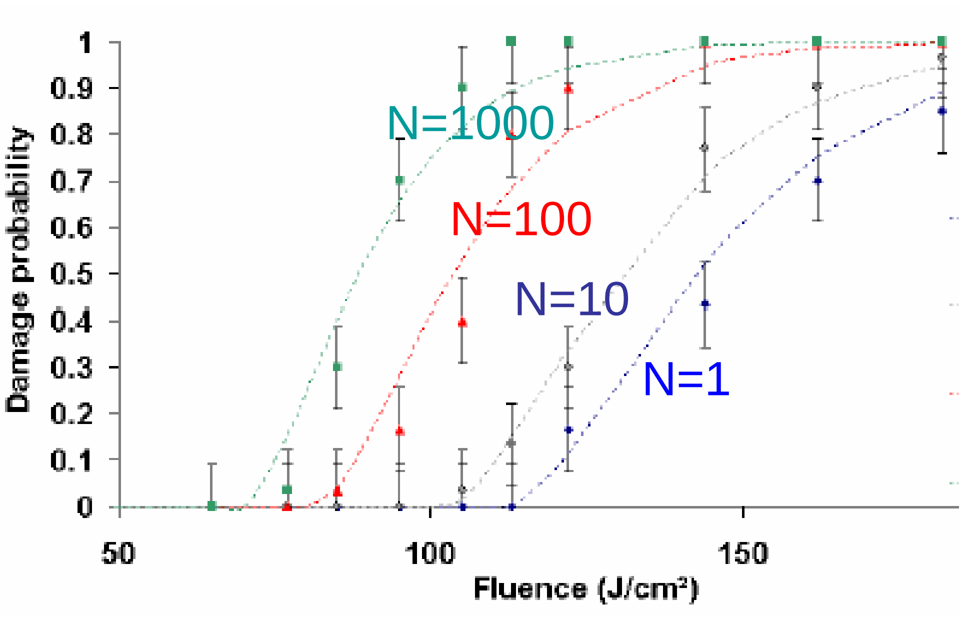
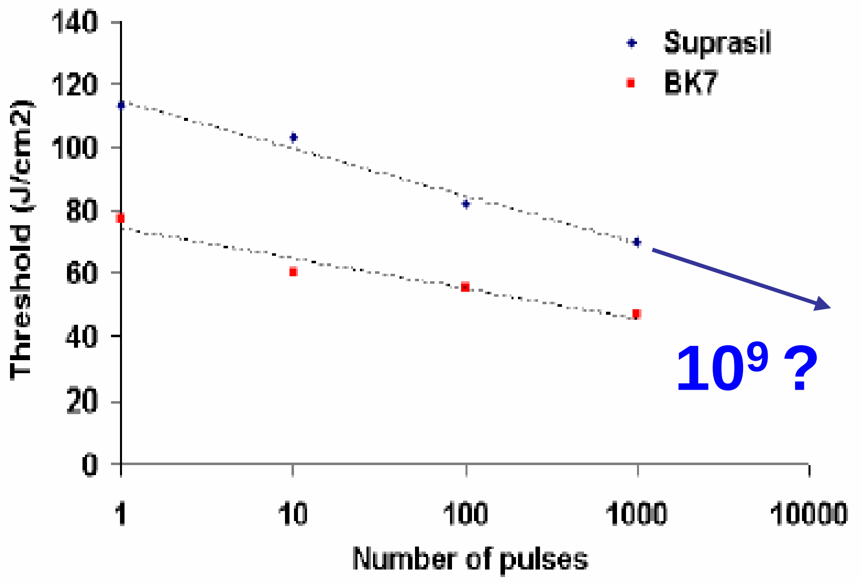
What about fatigue damage?

Laser induced damage studies on fused silica and BK7 using multiple pulses have shown possible fatigue damage

L. Gallais, Opt. Exp. **10** (2002).





Possible damage fatigue has been demonstrated for 1000 shots, but can we use this test to extrapolate to 10^7 or 10^9 shots?

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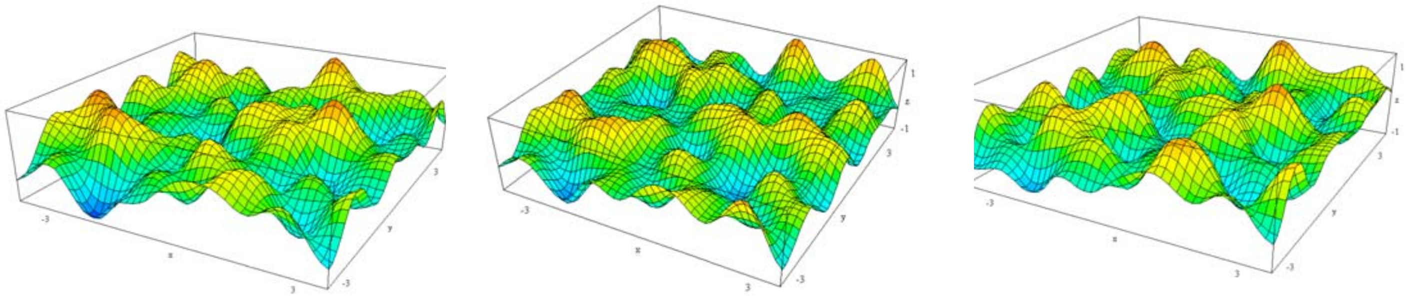
What is Max of N and it's relation to reliability?

If the beam changes from shot to shot (contrast) …



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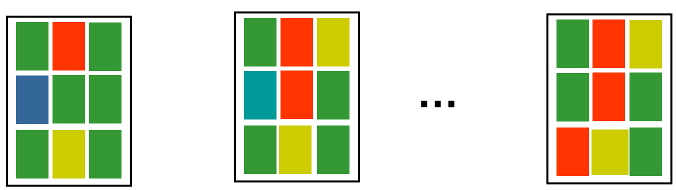
N shots



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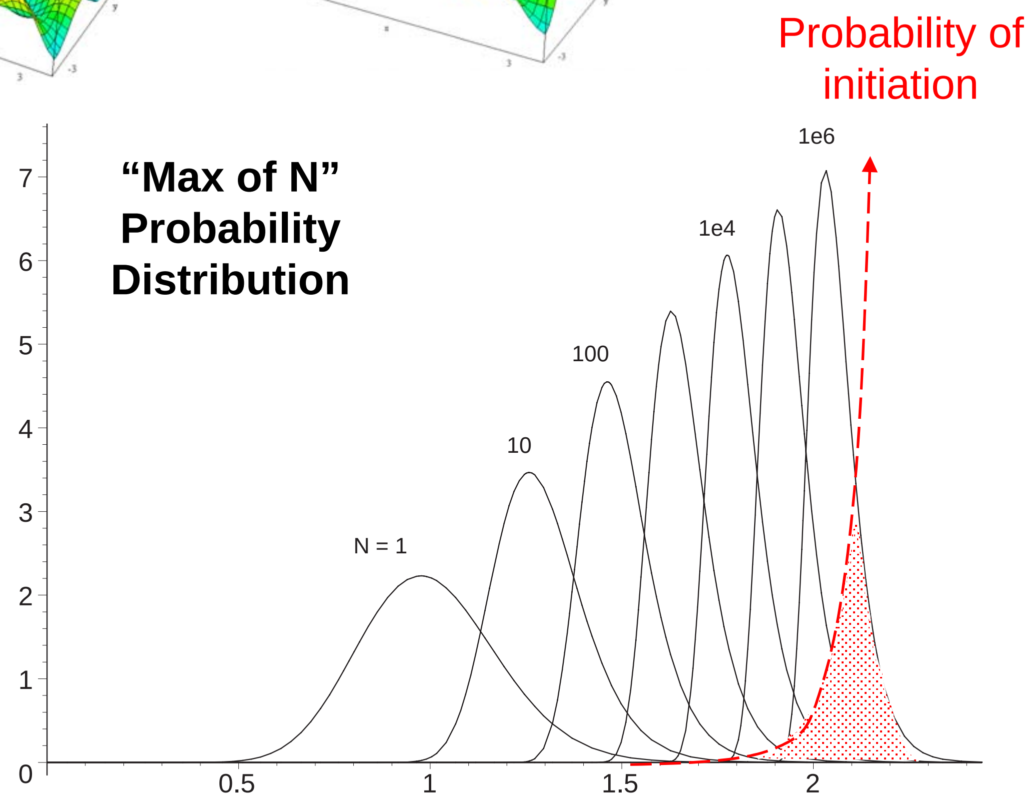
Max of N tally

Mean = μ

Standard deviation = σ

"Contrast" = σ/μ



J. Trenholme, LLNL (2005)

What’s our strategy?

<u>GOAL:</u> 10^9 shots without degradation in performance of various optics

Define initiation and growth specifications

Develop rules/models on damage initiation and growth

Perform damage testing to substantiate model

Define safe operational regimes based on model

Does safe operational regime meet performance requirements?

YES

Q&A

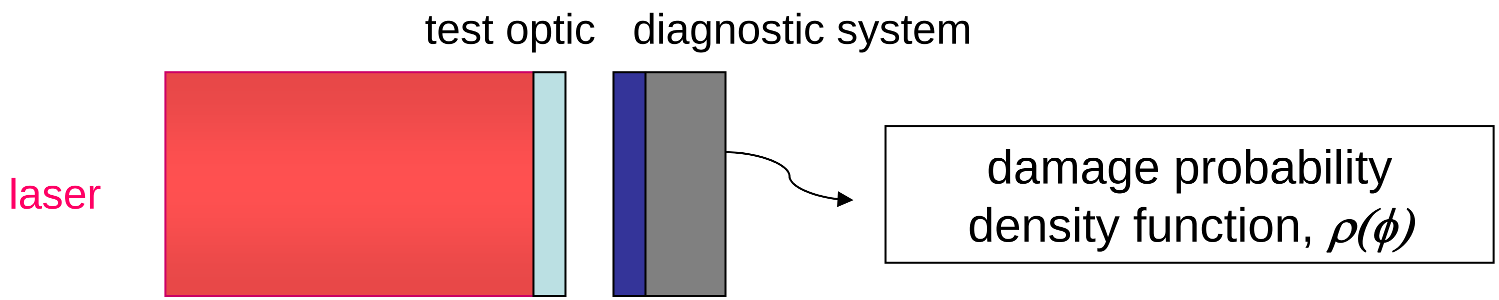
NO

Mitigation

Growth	Cutting	Grinding	Polishing	Coating	Operations

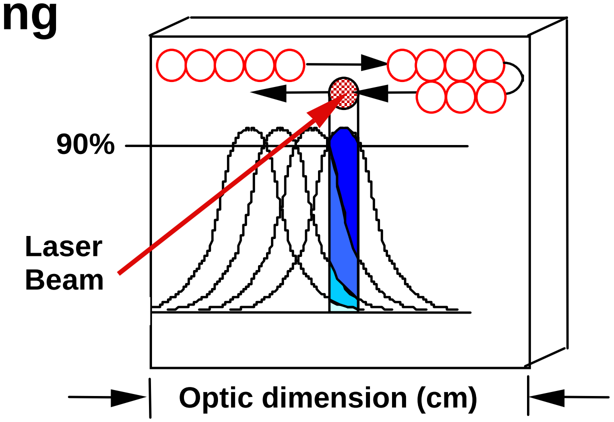
Damage tests

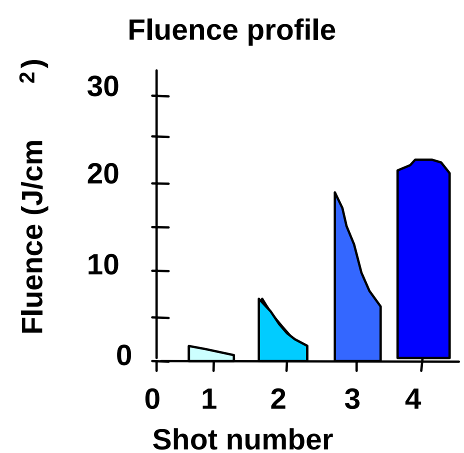
Full Aperture Beam Testing



- Requires high fluence with large enough aperture and good beam quality.

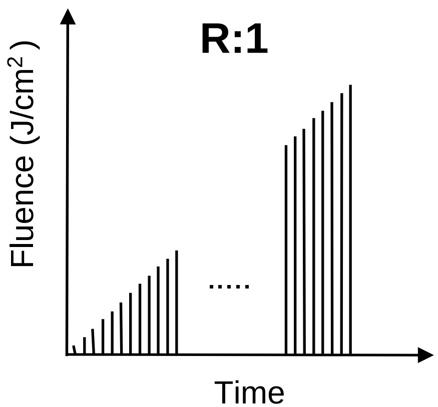
Raster testing

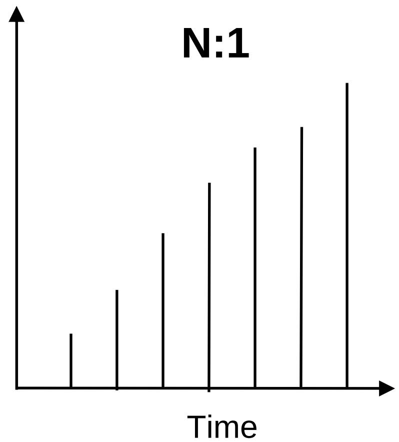


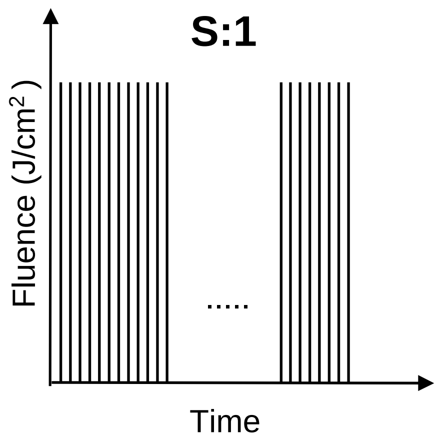


- Small beam size with pulses overlapping to test entire surface
- Each spot receives multiple laser illumination because of the overlapping

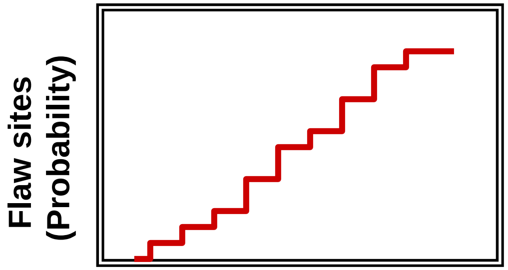
Small optic damage test

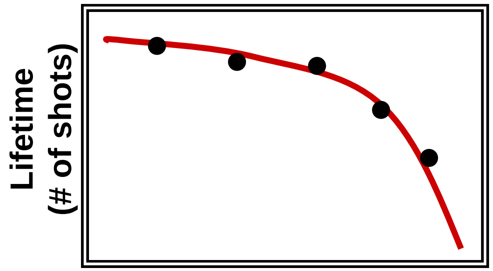


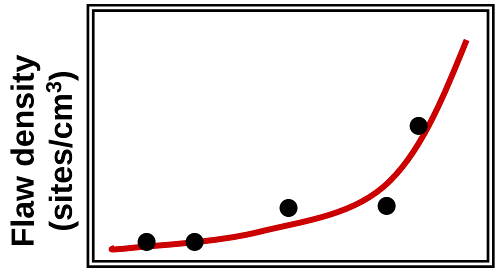




Purpose	Damage Threshold	Lifetime	Damage Probability
Fluence	Ramped	Set	Set
Spot	Move once damage	Same	New spot
Shots	Shot till damages	N shots per fluence	1 per spot







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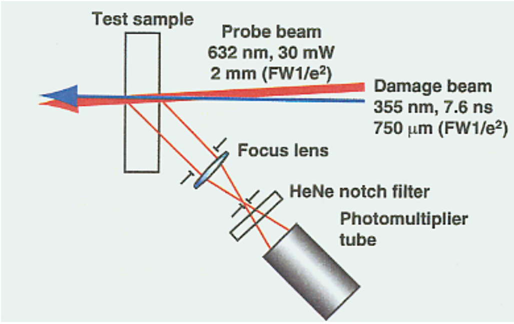
Diagnostics and Data Collection

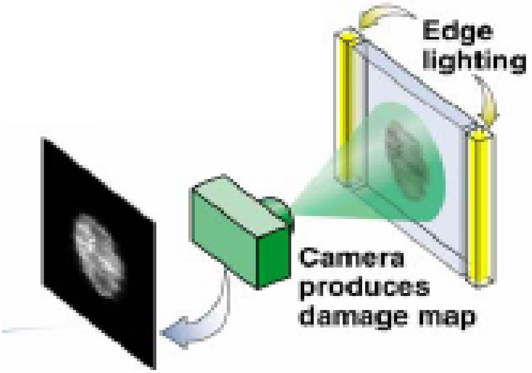
Flaw initiation can be detected a number of ways:



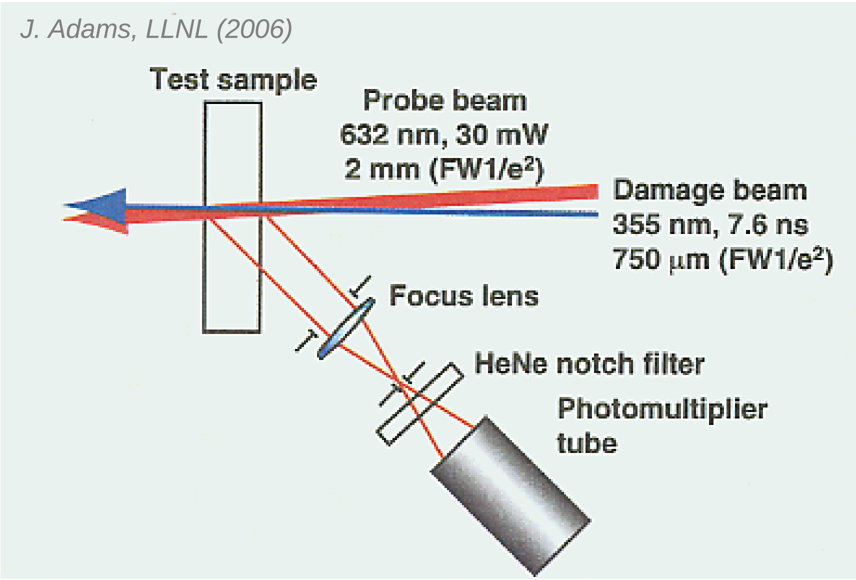
- **Laser probe scattering**
  - extremely sensitive
  - localized to the test region
  - differentiate between front surface, rear surface and bulk

- **Microscopy**
  - easiest way to recognize damage with camera (manual)
  - automatic scanning microscope (NEXIV)

- **DMS (Defect Mapping System)**
  - based on side-illuminating the test sample
  - quicker than scanning the test part



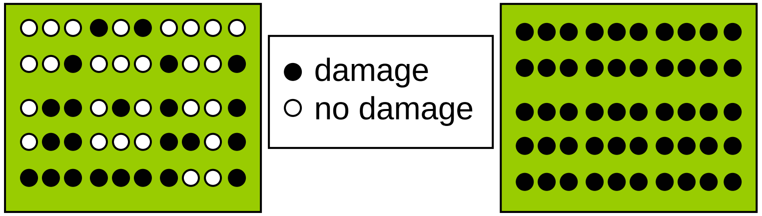
Laser Damage Testing (Zeus, LLNL)



S:1 test

R:1 test

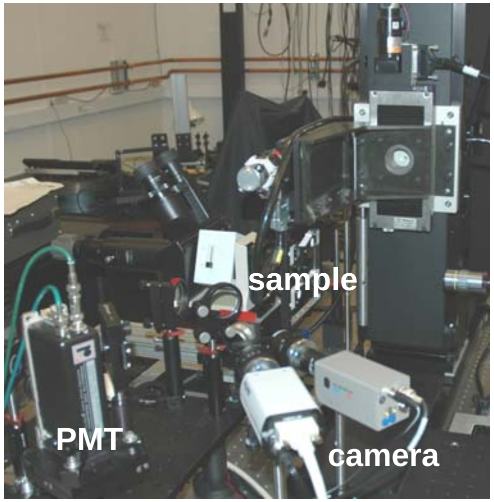
7 J/cm^2
9 J/cm^2
11 J/cm^2
13 J/cm^2
15 J/cm^2



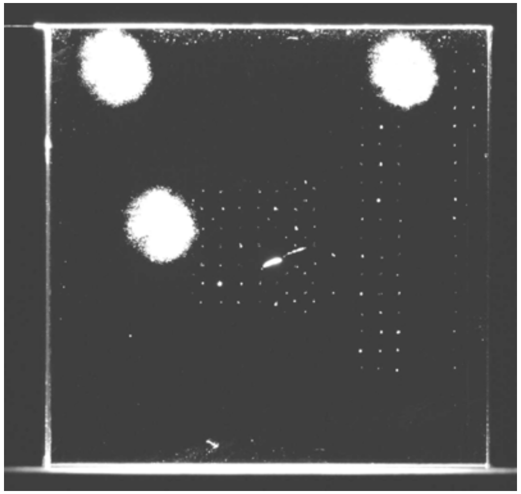
50 sites
5 fluences
damage density
“uncondition” case

50 sites
Ramped 0.2 J/cm^2

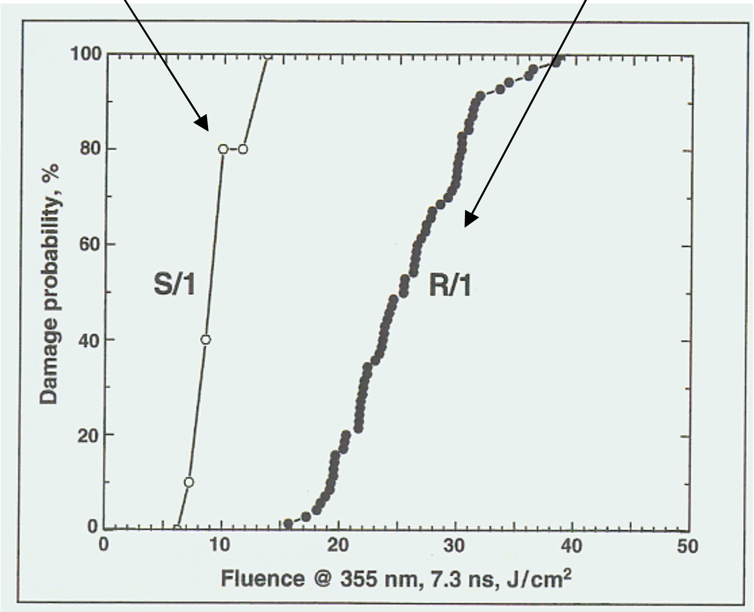
Best case
“conditioning” failure



In-situ diagnostics



DMS Result



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Q&A

NO

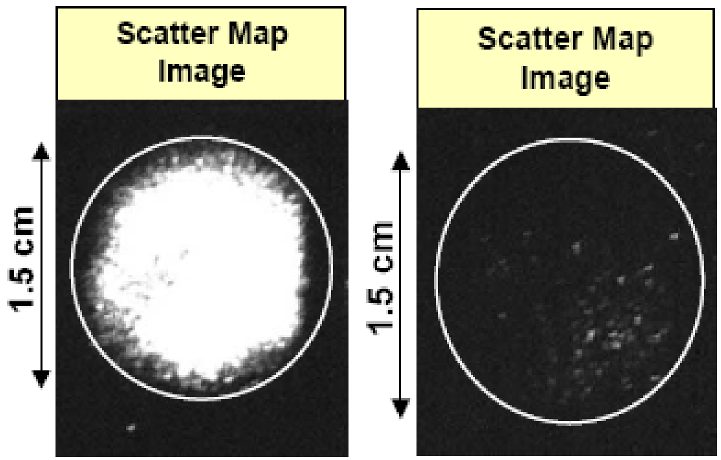
Mitigation

Growth	Cutting	Grinding	Polishing	Coating	Operations

Laser Conditioning

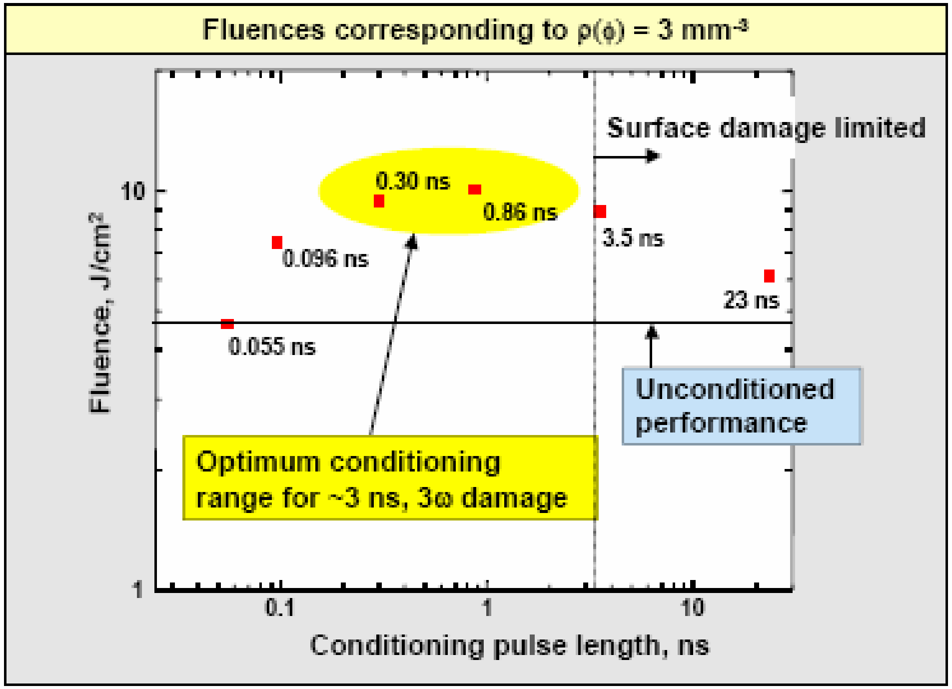
Laser conditioning – Pre-exposure of optic to laser fluence below damaging threshold, has been shown to improve the damage resistance of such as KDP/DKDP frequency conversion crystals.

Scatter map after 8 J/cm²



Unconditioned **Conditioned to 7 J/cm²**

Dependence on Conditioning Pulse Width



J. Adams, Boulder Damage. Sym. (2004).

Laser conditioning has substantially improve the performance of KDP and DKDP frequency conversion crystals for NIF

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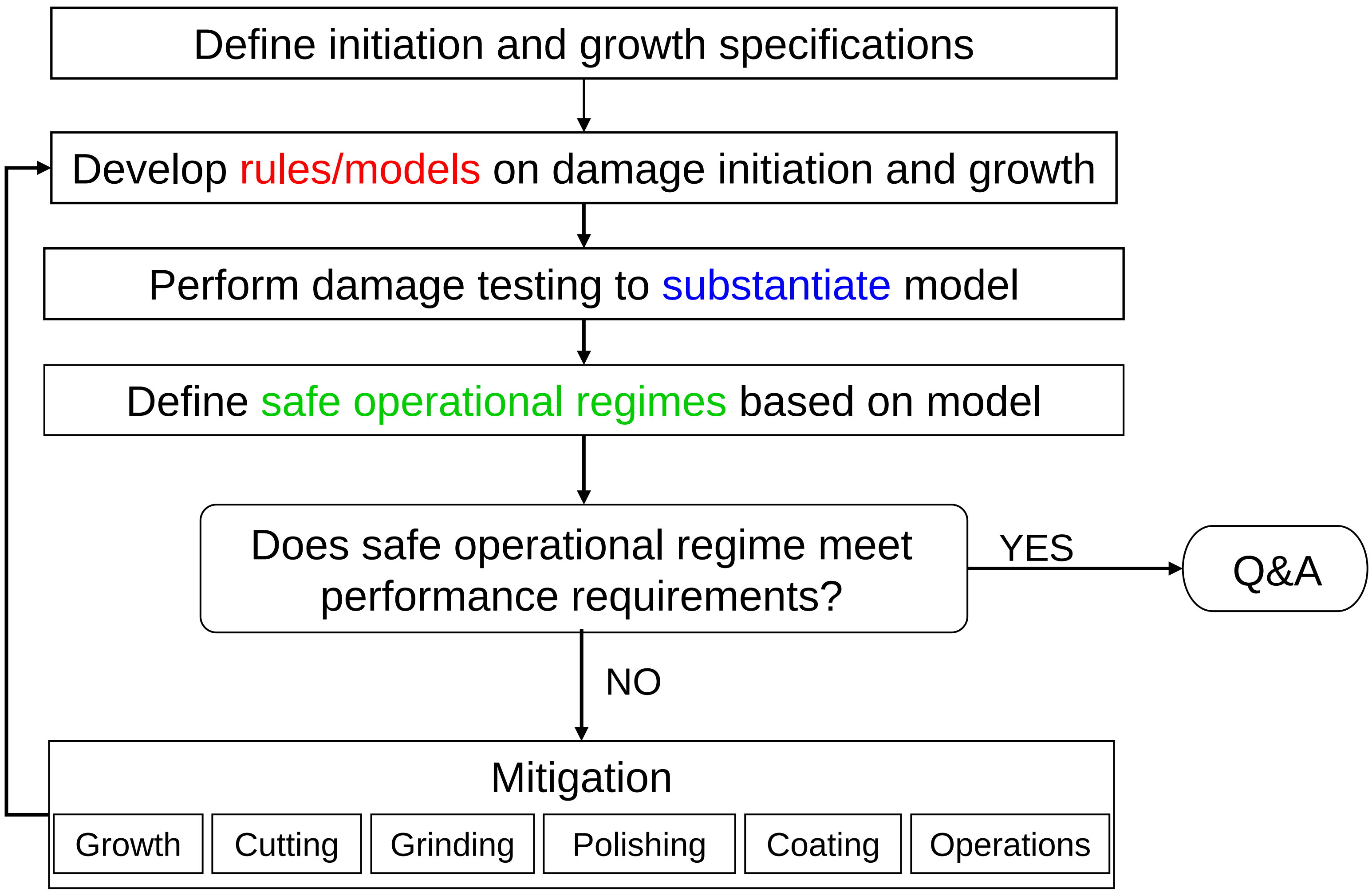
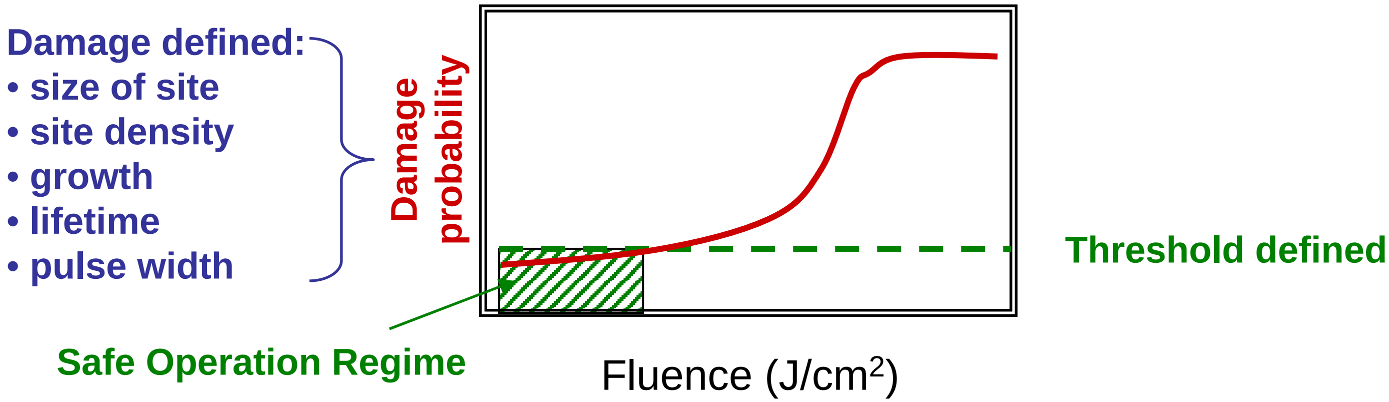


How do we provide qualification?

The test protocol's objective is to return a statistically-significant ***predicative*** model

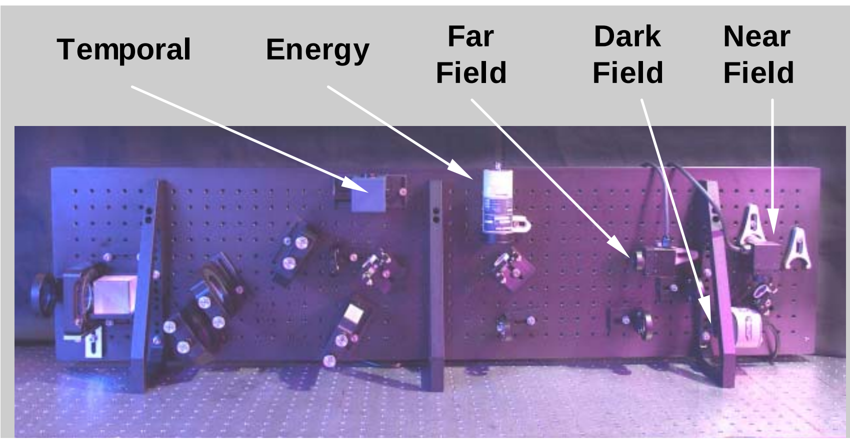


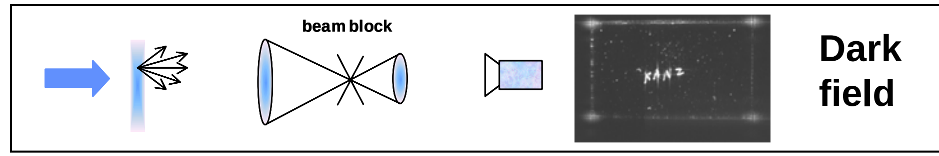
The model will only work if there is a ***qualification*** process to ensure quality

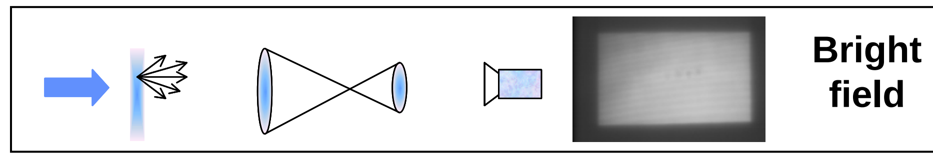
Category	**Parameters**	**Diagnostics for qualification**
Intrinsic Material	• vendor • growth parameter • raw material	• Absorption spectra • Scatterometry to detect inclusions • Fractology analysis
Material processing	• Cutting • Grinding/Polishing • Coating	• Transmission wavefront • Coating reflectivity curve • Raster scan at preset fluence
Material handling	• cleaning procedure • testing cleanliness/condition	• DMS • particle counter

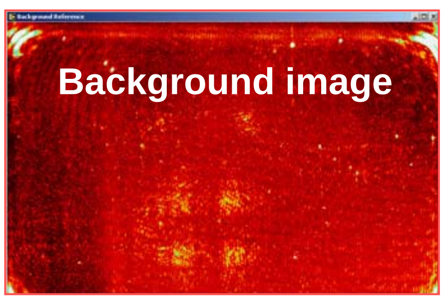
Providing Assurance

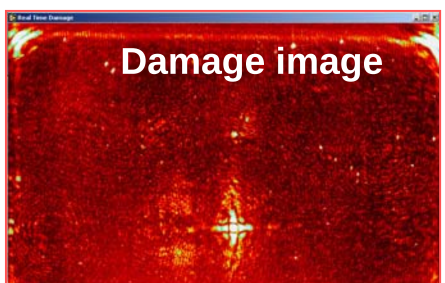
The Mercury Laser has implemented a state of the art damage detection system that is capable automatic, real time damage detection without user intervention – providing **Fail Safe Assurance**.

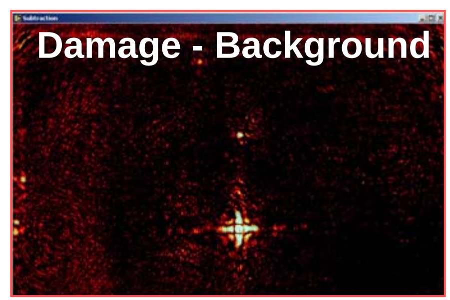


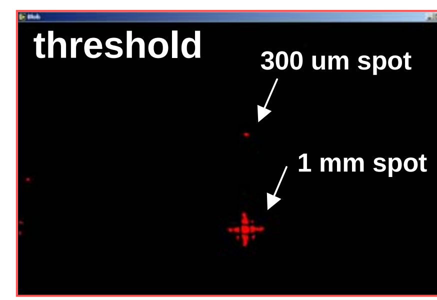












In-Situ diagnostics such as Dark Field Imaging and Analysis can help provide real time fail safe assurance.

Summary

Reliability of optical components for HEC DPSSL is a system engineering driven endeavor that must encompass

- **Prediction**: Offline damage testing, develop models.
- **Qualification:** Diagnostics and/or pre-qualification through raster scan.
- **Assurance:** In-situ diagnostic/fail-safe controls.

It is a ***difficult*** (i.e. detection of precursor sites) as well as ***time*** (i.e. optic fatigue damage) and ***resource*** consuming (i.e. sample cost) task.

Philosophy – strive to balance resources and caution so that the need to operate to run and gather data is weighed against the need of offline testing and R&D efforts to provide Q&A for safe operation.

Acknowledgement

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